Intensive Livestock Farming on New Zealand Hill Country Farms Creates Critical Source Areas of Potential Pollution

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Abstract

Nitrogen (N) from animal urine is a major potential water pollutant coming from grazed hill pastures in New Zealand. To ensure access to world markets, food must be produced sustainably. This research programme identifies reasons for and location of potential critical source areas (CSAs) of N which might lead to cost-effective, practical opportunities to mitigate N pollution. Urine sensors and GPS units for cows and ewes located urination events. Motion sensor data, a GIS and statistical models, made it possible to predict sheep resting and urination sites in response to variation in pasture mass and quality, slope, elevation and aspect. Aggregated urination events, or potential CSAs, were widespread at higher elevations within sheep paddocks. Because resting and urination zones were heterogeneously distributed, yet highly auto-correlated (r = 0.88), maps of resting areas alone predicted CSAs (R^2 = 0.82). Cattle resting and urination areas were more pronounced, with ~50% of urination events found in just 5-16% of paddock areas, generally in small, low-slope (≤12°) areas of steep paddocks and frequently near waterways. Models located cattle CSAs using GPS-resting and paddock contour data only. Greatest urinary N loads per cow urination occurred at night. Because these will mainly be excreted in campsites, >50% of daily urinary N will be excreted and leached from campsites. Farmers can probably access most of these small, low-slope areas, to target mitigation strategies to reduce N leaching. Contour maps alone might be sufficient to identify CSAs, while GPS tracking and mitigation records would prove resource consent compliance.

1. Introduction

Farmed hills have a high diversity of vegetation resulting from micro-environmental characteristics related to elevation, slope and aspect. Compared to low-slope land, soil on steep slopes are generally shallow, have a poor water holding capacity and can therefore generate greater overland flow that reduces soil fertility (Saggar et al., 1990; Lambert et al., 2000; Parfitt et al., 2009; Hoogendoorn et al., 2016). These factors affect plant species distribution and pasture growth production and, therefore, where animals prefer to graze (Rowarth et al., 1992; Lambert et al., 2000, 2003). Southern hemisphere south-facing slopes are cold and wet in winter and often have slow pasture growth rates compared to north-faces, but are warm and moist in summer, with high pasture growth rates. North-facing slopes are warmer in winter, but often hot and dry in summer. Summer-growing, highly nutritious legumes are sparse on north-facing slopes and these soils may be relatively more N deficient than on south faces. Without careful fence placement, stock transfer of plant nutrients from slopes to flatter areas and from cool to warmer areas (Saggar et al.,1990; Rowarth et al., 1992; Lambert et al., 2000) results in very high N leaching rates from flatter areas (Parfitt et al.,2009; Hoogendoorn et al., 2016).

McDowell & Srinivasan (2009) describe critical source areas (CSAs) for sediment, phosphate and faecal coliforms as zones in the landscape with excessive nutrient load that intersect an active hydrologic transport mechanism that poses a high risk for excessive pollutant export to surface waters. As urinary N is highly soluble it leaches to groundwater and is transported by sub-surface flow to streams and ponds (Ledgard 2001; White et al., 2001). Aggregation of excreta into CSAs in grazing systems is common in both hill country and lowland (White et al., 2001; Betteridge et al., 2012; Cai and Akiyama, 2016). Whereas 50-60% of excreted N is as urine, most excreted P is in faeces (Orr et al., 2012).To mitigate N pollution of water we must provide farmers with practical and affordable management tools to implement on their farm. This is challenging for farmers on steep hill country farms which can be hundreds to thousand hectares in size and which are extensively dissected by a mosaic of streams.

Satellite remote sensing is widely used to describe slope, aspect and elevation of landscapes and hyperspectral imaging is used to quantify biomass (BM; kg dry matter (DM)/ha) and nutrient content (e.g. Lilienthal et al., 2007; Kawamura and Akiyama, 2012). Defining why and where animals congregate (stockcamps), and the amount of excreta deposited in these camps is now possible using cheap GPS tracking devices on cattle and sheep (Betteridge et al., 2010a; Betteridge et al., 2012); and urine sensors for female cattle and sheep can count and log the number of urination events (Betteridge et al., 2010b; Betteridge et al., 2012; Benke et al., 2015). A new sensor estimates the amount of cows' urinary N excreted in each urination event (Betteridge et al., 2013b; Shepherd et al., 2016) which enables CSAs within grazed paddocks to be ranked for their relative risk to stream pollution. This is especially important with cattle-grazed pastures which leach twice as much nitrate-N/ha as sheep- and deer-grazed pastures, on an equivalent DM intake/ha basis (Hoogendoorn et al., 2011).

This review describes NZ hill country research linking animal behaviour to landscapes over short time scales, within 0.5 to 11 ha paddocks. Predictive models are described that enable farmers to map CSAs and strategically manage grazing to mitigate potential N pollution. The overarching goal is to enable sustainable intensification of food production in hill country (Roche et al., 2016).

2. Methods and Materials

Hand-held, GPS and hyper-spectral imaging devices were used to create digital elevation models (DEM) defining slope, aspect and elevation of grazed paddocks and maps of BM and pasture mineral mass variability as potential attractants to grazing sheep (Trial 1). At other sites, DEM and animal sensor data were the main inputs for model development.

2.1. Female sheep and cattle urine sensor *(Type I)*

This device, anchored in the vagina, detected each urination event by a change from ambient to body temperature as urine flowed over it (Fig.1a,b). Concurrent GPS tracking showed the location of each urination event (Betteridge et al., 2010a, b). These custom-made urine sensors and GPS units were cheap and easily fitted to animals. Animals could be left to graze in large steep or flat paddocks for the duration of the battery's power supply.

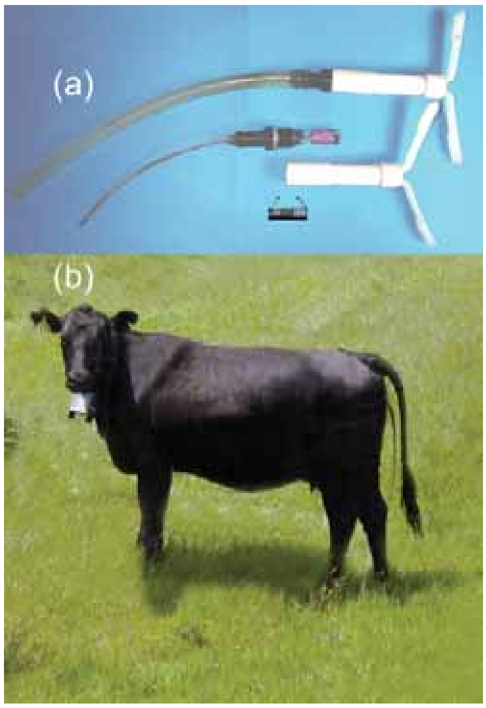

Fig.1. (a) Upper picture: is the complete sensor, with the white section inserted into the vagina; lower image shows sensor components (left to right: thermistor, circuitry and battery, waterproof pipe with soft silicon 'wings' to retain sensor within the vagina. Temperature is measuresd as mV.
(b) lower picture: sensor seen under cow's tail.

2.2. Female urine sensor *(Type II)*

This larger, heavier urine sensor was developed for cows to quantify urine volume and urinary N concentration [N] (Fig.2b; Betteridge et al., 2013b; Shepherd et al., 2016). Urine flow through the sensor (Fig.2a) creates a head of pressure which is continuously logged. Volume is determined by the area under the curve of an 'event duration v. pressure' graph. Urinary N concentration is estimated using a calibrated refractive index sensor (MISCO, Ohio, USA). The sensor, fixed to a cow cover (Fig.2b), is suspended under the tail, and the 'urine collector' is glued over the vulva to entrain urine into the sensor, without faecal contamination.

2.3. Research studies

To determine the number of urinations and their distribution within paddocks, grazing trials were conducted on farms near Lake Taupo and near Palmerston North, NZ. Four sites comprised flat and steep zones of 'browntop (*Agrostis capillaris*)/ ryegrass (*Lolium perenne*)/white clover (*Trifolium repens*)-based pastures. Monitored animals grazed within larger mobs of sheep or herds of cattle. Trial 5 was with dairy cows on flat land grazing ryegrass/ white clover pastures.

2.3.1 Trial 1 (Betteridge et al., 2008; Kawamura et al., 2009): A Geographic Information System (GIS) array of 10 m* 10 m cells overlying the 2.8 ha paddock contained DEM layers; BM and pasture quality; animal location (sum time spent in grid cells - T_{min}) and urination event (sum events in grid cells – U_{events}) data, to answer the question "is sheep urine distribution related to variation in pasture BM, masses N, P, K and S nutrients, slope, aspect or elevation?" A flock of 80, 3-year-old sheep grazed the paddock for 6 days in autumn, with 20 sheep fitted with a GPS and *Type I* urine sensor. Using a real-time kinematic GPS, point heights were streamed across the paddock. Hyper-spectral radiometer readings (400-2400 nm) were taken at 330 approximately equal spaced sites to determine pasture BM and pasture N, P K and S masses. Partial Least Square regression (PLS) full-spectrum analysis of pasture BM and quality spectra provided GIS polygon cell data for mapping each parameter's spatial variability. Geographically Weighted Regression (GWR) and Ordinary Least Squares (OLS) regression models were used to determine relationships between T_{min} and U_{events} in relation to pasture and DEM variables.

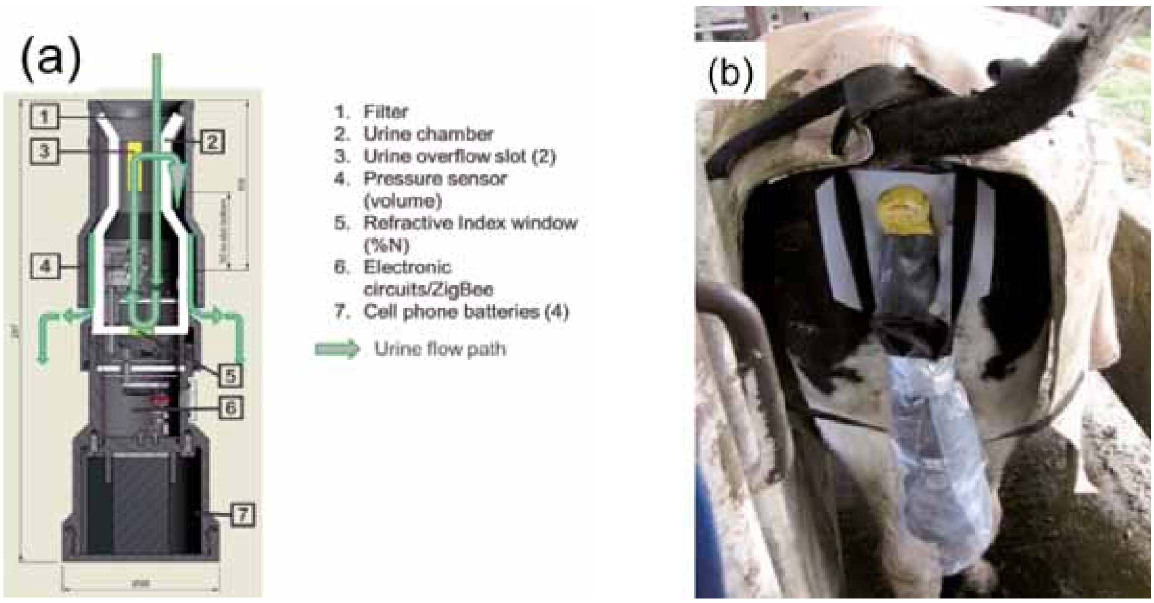

Fig.2. (a) *Type II* urine sensor showing the path of urine flow within chamber (2) and the refractive index sensor (5) that measures [N]. (b) Urine sensor attached to cow cover (black straps) with urine collector (yellow object) glued over the vulva. Grey patch assists retention of collector on the animal and polythene sleeve covers the sensor (a).

2.3.2. Trial 2 (Betteridge et al., 2010a)

Concurrently and just 1 km from Trial 1, within a 70 cow+calf herd, 20 beef cows were fitted with a *Type I* urine sensor and a GPS, grazed a steep 11 ha paddock over 7 days. The Paddock DEM was formed as in Trial 1. Pasture BM was not recorded, but was more than enough to provide the animals' needs. Grid cell T_{min} and U_{events} data were overlaid on the Paddock's DEM for determining spatial relationships.

2.3.3.1. Trial 3a (AgResearch's *Ballantrae* Research Farm near Palmerton North): Because farmers won't know animal movements or location of urine patches during a paddock's grazing, a surrogate parameter for predicting where they rest and urinate was needed. Twenty, 20-month-old female cattle were fitted with a *Type 1* urine sensor, motion sensor and GPS and monitored over 5 days while grazing a steep, 0.7 ha pasture. The paddock DEM was manually determined with a GPS. In the first instance, a *lying time* model (T_{min}) was created using independent variables, location (Eastings, Northings), slope, aspect and elevation (Betteridge et al., 2012).

2.3.3.2 Trial 3b A refined *resting* model (lying + standing time) based on a *threshold velocity of travel* within grid cells was developed with data from Trial 3a , and then tested with Trial 2 and Trial 3 data using just average velocity, and normalised location and DEM data. Normalisation makes resting time data compatible across paddocks. To confirm our concepts of CSAs in hill country, 83 soil samples were taken from GPS-located sites (campsites, shade trees, water trough, gateways and slopes) across 8 paddocks, with the Olsen P test used as the proxy for confirming nutrient transfer off slopes to flat areas (Betteridge et. al., 2013a).

2.3.4. Trial 4 (Massey University, Palmerston North)

Nine non-lactating cows were monitored for 11 days during winter while being offered a strip of new pasture each morning. Pasture was eaten in 2-3 hours. Cows were fitted with a GPS and *Type II* urine sensor and remained in the paddock once the strip of pasture had been eaten. Urinary nitrogen [N] and urine volume were used to calculate *N load* in each urination event (Betteridge et al., 2013b).

2.3.5. Trial 5 To estimate N leaching at the paddock scale, based on daily cattle data, Li et al. (2012a) used [N] and urine volume data of grazing beef steers (Betteridge et al., 1986) to develop a framework to assess the effects of varying cattle [N] and volume on N-leaching loss. Varying urine patch areas (urine spread) in relation to changing urine volumes were estimated and annual urinary N depositions were estimated. The model was driven by animal grazing days supported by pasture production (animal•days/ha/yr) and the average urine deposition events/animal/day. The N leaching from heterogeneous urine patches were scaled up to paddock level based on the frequency distribution of a range of urine patches. Measured [N] and volume data (Trial 4) were used within the framework to estimate the N leaching from Taupo pastures to demonstrate the effects of actual urine volumes and actual [N] on N leaching from grazed pastures.

3. Results and Discussion

3.1. Trial 1 (Betteridge et al., 2008)

Ordinary Least Square (OLS) regression models assume uniform variance amongst data across the paddock, but pasture BM and mineral mass data were highly heterogeneous and strongly auto-correlated. Therefore the GWR, using first derivative regression (FDR) data, gave better estimates of spatially varying parameters for BM, and mineral masses within the paddock. The R^2 value of 0.84 between actual and predicted BM, and similarly high R^2 values for N, P and S masses (kg/ha), were good for this difficult environment. Average number of sheep urination events was 20.6, but for sheep-within-days, ranged from 6 to 35. Sheep moved an average 2.6 km/day (1.3 – 4.1 km). Compared to low slope areas, sheep spent little time (T_{min}) on the top of hills or on steep sidelings. Low slope and flat areas were where their urination events (U_{events}) were concentrated (Fig.3). T_{min} and U_{events} were strongly correlated (r = 0.88), with each being less strongly correlated to *Elevation. Slope* was negatively correlated to T_{min} indicating sheep prefer to on flatter areas. Individual sheep were observed resting on small flat areas on hill slopes.

Although BM and mineral masses were strongly correlated, only S_{mass} was significantly correlated with T_{min} and U_{events} (r = –0.36 and –0.35 respectively). Using the backward stepwise selection method with OLS regression to predict spatial distribution of T_{min}

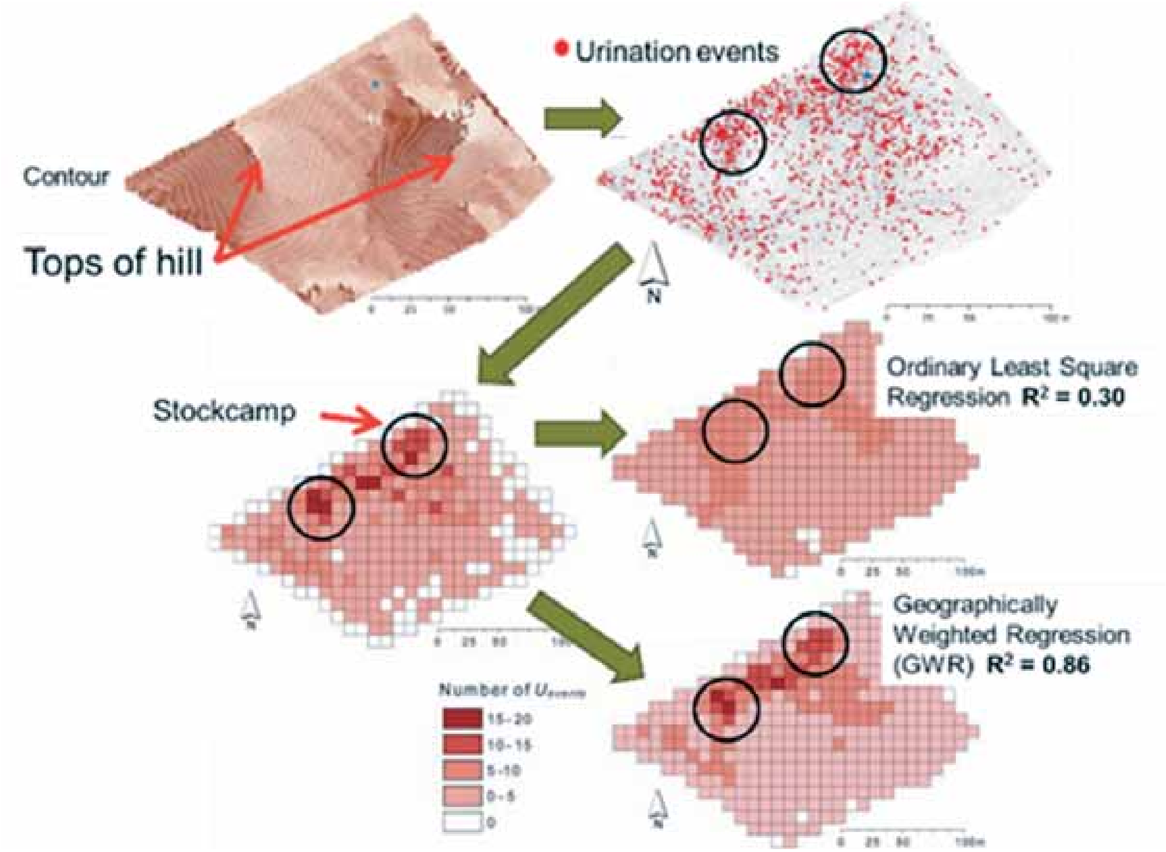

Fig.3. Inputs for predictive Ordinary Least Square and Geographically Weighted Regression models for mapping sheep urine distribution on a steep 2.86 ha paddock on a Taupo farm.

and U_{events} showed elevation, aspect and S_{mass} strongly influenced both T_{min} and U_{events} distribution, whereas only T_{min} was significantly influenced by Slope. The GWR predictive model with 8 independent variables gave much better goodness-of-fit (R^2 = 0.86 & 0.87) values for T_{min} and U_{events} respectively, than the OLS prediction (R^2 = 0.29 & 0.29). A simple regression to predict U_{events} based on T_{min} (R^2 = 0.75) showed T_{min} alone, might be sufficient to locate urine CSAs. The benefit of using GWR over OLS is seen in Fig. 3.

3.2. Trial 2 (Betteridge et al., 2010b)

Mean number of cow urination events was 12.3/day. The median slope of 10 m × 10 m polygon grid cells with at least one urination event recorded was 13.2° while the average slope of all these cells was 8.0°. This supports our contention that cattle camp on low slope areas in steep hill country.

To define where 9 cattle camped during the 4 grazing days (data of <24 h continuity were omitted) in this 11 ha paddock, a speed limit of ≤0.5m/sec within polygon cells with ≥2 urination events was set. The aggregation of cells in Fig.4a indicates cattle "camped' (rested and urinated) predominantly in low elevation, flat areas of the paddock and close to water troughs. The accumulated T_{min} regressed against U_{events} revealed a moderate correlation (r = 0.54). This correlation was lower for cattle than sheep (Trial 1) reflecting that; (1) there are five times more animals/ha in the sheep compared to cattle in the present trial, when stocked at the same stocking rate (sheep stock units (SU)/ha) and; (2) each sheep urinates ~20 times compared to cattle ~10 events/day. In this cattle paddock, 5% of the paddock contained 41%, and 10% of the paddock contained 61% of all urination events excreted during the grazing period.

As in Trial 1, it appears that a contour map could be used to predict the location of half of all cattle urine patches in steep hill country.

Fig.4. (a) Urine distribution by 9 cows grazing over 4 days in this steep, 11 ha paddock. Spots show urine patches; squares enclose groups of 10 m* 10 m cells in which velocity was <0.5 m/sec and in which there were ≥2 urination events; Circles show water troughs. (b) 3-D representation of the East end of Fig.4a. where histogram height within cells increases with number of urine patches and transistion from green to red shows increasing time spent in cells.

3.3.1. Trial 3a (Betteridge et al., 2012)

Cows urinated an average 9.0 events, lay down 45%, grazed 33%, stood 14% and walked 3% of the day. T_{min} was correlated with U_{events} (r = 0.64), with slope (–0.34) and dung deposition (0.49, manually mapped at the end of grazing). As in other trials, cattle lay down mainly in the only low-slope (0–12°) areas of this steep paddock. The correlation between T_{min} and U_{events} increased when *lying* and *standing* times were combined into a 'resting' variable (Fig. 5a). Near Neighbour Regression (kNNR), and the Generalised Additive Model (GAM), using associated grid values of Aspect, Slope, Elevation, Location (Eastings and Northings), gave the best prediction of T_{min} within 5 m* 5 m grid cells (Fig. 5b). Thus, knowledge of the paddock's contour features and Eastings and Northings could be used to predict resting places, and therefore, locate potential CSAs containing a high proportion of all urination events (and faeces) (White et al., 2001; Betteridge et al., 2012; Orr et al., 2012; Draganova et al., 2016).

3.3.2. Trial 3b (Betteridge et al., 2013a)

The *resting threshold model* determined the upper GPS threshold velocity of 0.11 m/sec, to represent when a cow was at rest (standing/lying). This approach dealt with 'misclassification' errors, random GPS errors, movement 'created' when disaggregating GPS travel speed between adjacent grid cells, and extended resting time intervals when no GPS readings were logged. Data normalisation was shown to be important when developing a generalised model for use over farms and regions.

It is clear in Fig.6 that the majority of cattle urine patch areas match the proxy resting time contours, especially where there were high densities of urine events (Betteridge et al., 2013a). In fact, of the grid cells with at least two urine events recorded, 86% also recorded lying events. When the urination events and lying times were accumulated over a 15 m × 15 m grid (formed using adjoining 5 m × 5 m cells), the correlation between urination events and lying time was r = 0.68. Of these larger cells with at least one urination event, 75% also recorded lying events. On a lowland dairy farm T_{min} was also correlated with U_{events} (r = 0.49; Draganova et al., 2016). Therefore, we suggest that the *resting threshold model* is a simple and efficient methodology for identifying potential CSAs within a paddock, based on animal GPS velocity and DEM data.

Soil Olsen phosphate data from obvious campsites, gateways, water troughs and under trees averaged 50.7 mg P/kg soil compared to just 13.4 mg P/kg soil on slope areas, confirmed the long-term accumulation and depletion of P transfer, via faeces, respectively. The strong relationship between faecal and urine deposition from this study and that reported by White et al. (2001) shows that areas around trees, gateways and water troughs within the paddock (White et al. , 2001; McDowell 2006; Draganova et al., 2016) need to be added to any CSA map based on DEM inputs alone.

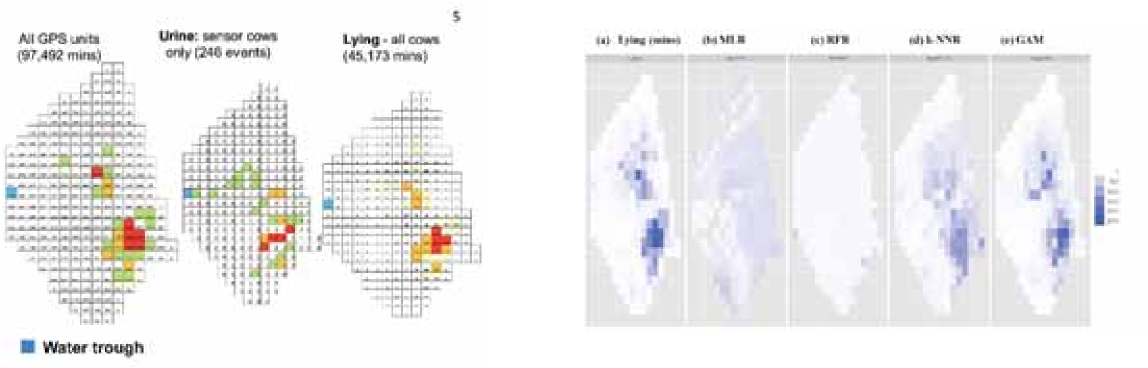

Fig.5. (a) Colour coding of 10 m * 10 m GIS grid cells show increasing values from green throughred of total minutes, urination events (urine sensor cows only) and lying time within cells of 20 cows over 5 days on this 0.7 ha steep hill paddock; (b) Actual lying time and predicted lying time based on Multiple Linear Regression(MLR), Random Forest Regression (RFR), Nearest Neighbour Regression (k-NNR), and Generalised Additive Model (GAM) models using a cross-validation test.

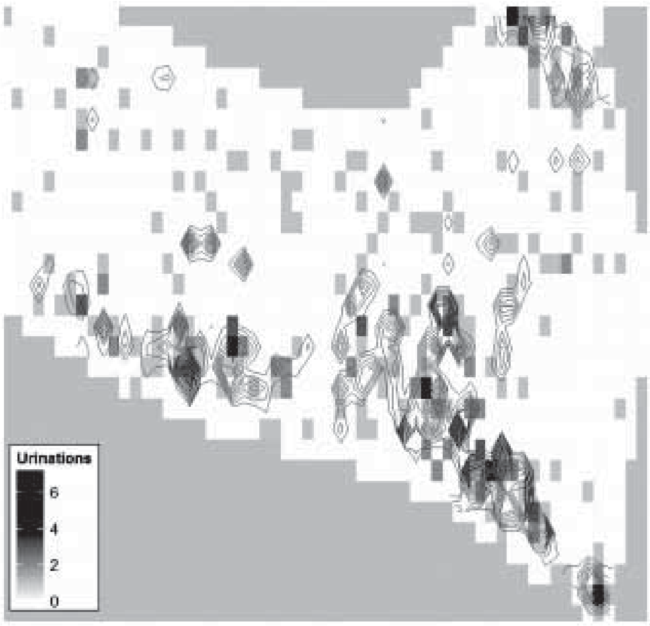

Fig.6. Contour lines created by the *Resting Threshold Model* showing where cows might camp in the small section of hill pasture shown in Fig.4b. Grey scale grid cells show the number of urination events known to have beenexcreted within grid cells.

3.4. Trial 4

Average volume of urination event was 2.1 L (SD 1.32) and ranged between 0.30 L and 7.83 L/event and average [N] was 0.95 g N/100 ml urine (SD 0.53), and ranged between 0.12 and 2.47 g N/100 ml (Betteridge et al., 2013b). Misselbrooke et al., (2013, 2016) used *Type II* sensors on grazing beef and dairy cattle in the UK and found similar urine characteristics.

At around 1-2 AM and at sunrise there was synchronised urination activity (Fig. 7). Most high N-load events occurred at night, though some smaller-load events sometimes followed large N-load events at these times. A high urination frequency occurred when cows were shifted to new pasture, but the N-loads were invariably small. Urinary N-loads/event became larger after grazing finished mid-morning. The majority of high N-load urination events in this trial occurred at night, which is probably true on all cattle farms. Hirata et al., (2011) also measured larger depositions of urine (and faeces) during the night than daytime, with frequency of deposition being higher in daytime. If so, such events in hill country would typically occur in stock camps on low-slope land predominantly at the bottom of the hill. Therefore, at the paddock scale, greatest N leaching

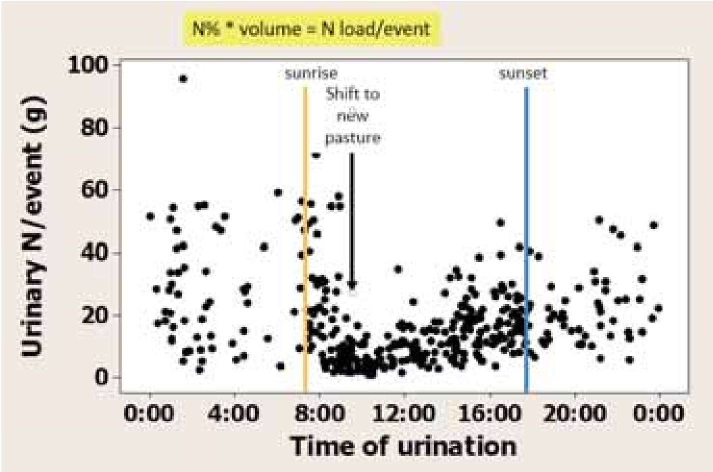

Fig.7 N-load of 9 non-lactating cows grazing a strip of fresh pasture each day over 11 days during winter. Cows wore a *Type II* urine sensor.

will occur under stock camps rather than from urine patches excreted during daytime. These daytime urination events will more likely be distributed across the paddock during grazing. Increasingly, lowland dairy farmers who are winter strip-grazing their cows will feed this pasture for 2-3 hr and then remove them to a holding pad. Our data suggests N loads will be small during this grazing period, only increasing once pasture is digested and surplus N excreted in urine once on the pad. Thus, the risk of N leaching from the grazed strip would be low, while the urinary N excreted on the holding pad could be managed in some manner to minimise N leaching (Di and Cameron 2016; Betteridge et al., 2013b).

3.5. Trial 5

A Case Study showed that if campsites received 30% of all urination events on just 3% of the paddock area, 37% more N would leach from "the whole paddock" compared to random application of the same amount of N (Li and Betteridge 2012b). Using model simulations of 2 years grazing followed by 2 years cropping, Hutchings et al. (2007) also reported greater rates of nitrate leaching when heterogeneity was included in the model, rather than the same amount of urinary N was applied uniformly over the paddock. Overlapping urine patches within the campsite was one main driver of increased leaching rate, as were urine patches with high N-loads. This is because N leaching increases exponentially as N load in the soil increases (Ledgard, 2001; McGechan and Topp, 2004; Shorten and Pleasants, 2007).

Many hill country farms have small areas on which they grow winter-fed crops and pastures. As cattle usually remain there for 2-3 months, these areas should be prioritised for implementing strategies to reduce N leaching (Betteridge et al., 2011).

To meet audit requirements of a Regional Authority, the farmer may need only print the farm's DEM showing zones of ≤12° slope, fence-lines, trees and streams and the GPS track of the farm vehicle used when applying the mitigation "tool".

If five sheep eat the same amount of N and excrete a similar amount of urinary as one cow, urinary N would be spread amongst 100 sheep urine patches compared to 10 urine patches for the cow (Betteridge 2010a). Thus the N load/urination event would be substantially higher in cattle, than in sheep, and be more clearly defined in cattle stockcamps than in the more diffuse, and smaller, sheep stockcamps (Betteridge et al., 2010a). This may explain why nearly double the amount of N leached from under cattle-grazed, than under sheep- or deer-grazed pastures stocked at a similar SU equivalence/ha (Hoogendoorn et al.2011). These findings make it clear that mitigation of N leaching on hill farms should be aimed at cattle-grazed paddocks.

Conclusions

New technologies have enabled the identification of urine distribution within grazed paddocks. Cattle create a greater N pollution threat to streams than sheep, so greatest emphasis on N leaching mitigation should be on cattle grazed pastures. It could be cost effective and practical for farmers to target these campsites with mitigation tools because only 5-15% of steep hill country might be used as campsites, yet contain ~50% of all urination events and more than 50% all excreted urinary N.

These zones could be determined from contour maps showing only the 12° isohyet to identify potential CSAs. Additional smaller CSAs under trees, around water troughs and gateways should also be targeted.

Many potential management strategies to decrease N loss from the urine patch are still at the proof of concept stage with few actually deployed on the farm (Monaghan et al., 2007; McDowell & Srinivasan 2009; Betteridge et al., 2011). Further research is required to integrate these into farm management systems (Selbie et al., 2015).

References

Augustine, D. J., D.G. Milchunas and J. D. Derner (2013) Spatial redistribution of nitrogen by cattle in semiarid rangeland. Rangeland Ecology and Management, 66:56–62.

Benke, K. K., F. Sheth, K. Betteridge, C. J. Pettit and J. P. Aurambout (2015) Application of geovisual analytics to modelling the movements of ruminants in the rural landscape using satellite tracking data. International Journal of Digital Earth, 8: 579–593.

Betteridge, K. and W. G. K. Andrewes (1986) Intake and excretion of nitrogen, potassium and phosphorus by grazing steers. Journal Agricultural Science, 106, 393–404.

Betteridge, K., K. Kawamura, D. Costall, M. Carter, C. Hoogendoorn, W. Griffiths and Y. Inoue (2008) Tools to determine impact of animal behaviour on nitrogen leaching and nitrous oxide emissions. Occasional Report No. 21, Proceedings of the workshop Carbon and Nutrient Management in Agriculture, L. D. Currie and L. J. Yates (Eds.), pp. 286–298.

Betteridge, K., D. Costall, S. Balladur, M. Upsdell and K. Umemura (2010a) Urine distribution and grazing behaviour of female sheep and cattle grazing a steep New Zealand hill pasture. Animal Production Science, 50: 624–629.

Betteridge, K., C. Hoogendoorn, D. Costall, M. Carter and W. Griffiths (2010b) Sensors for detecting and logging spatial distribution of urine from grazing cows and ewes. Computers and Electronics in Agriculture, 73: 66–73.

Betteridge, K., F. Li, D. Costall, A. Roberts, W. Catto, A. Richardson and J. Gates (2011) Targeting DCD at critical source areas as a nitrogen mitigation strategy for hill country farmers. In: Adding to the knowledge base for the nutrient manager, Currie, L. D. and C. Christensen (Eds.) , Massey University, Palmerston North, Fertilizer and Lime Research Centre. 11 pages.

Betteridge, K., S. Ganesh, D. Luo, K. Kawamura, D. Costall and R. Yoshitoshi (2012) A methodology for determining critical source areas of nitrogen in grazed hill pastures. In: Advanced Nutrient Management: Gains from the Past - Goals for the Future, Currie, L. D. and C. Christensen (Eds.), Massey University, Palmerston North, New Zealand, Fertilizer and Lime Research Centre. 10 pages.

Betteridge, K., D. Costall, D. Lou, S. Ganesh and H. Sun (2013a) Development of a critical source area prediction model of nitrogen leaching. In: Accurate and efficient use of nutrients on farms. L. D. Currie and C. L. Christensen (Eds.), Occasional Report No. 26. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 8 pages.
http://flrc.massey.ac.nz/publications.html.

Betteridge, K., D. A. Costall, F.Y. Li, D. Luo and S. Ganesh (2013b) Why we need to know what and where cows are urinating – a urine sensor to improve nitrogen models. Proceedings of New Zealand Grassland Association, 75, pp.119–124.

Cai, Y. and H. Akiyama (2016) Nitrogen loss factors of nitrogen trace gas emissions and leaching from excreta patches in grassland ecosystems. A summary of available data. Science of the Total Environment, 572: 185–195.

Di, H. J. and K. C. Cameron (2016) Inhibition of nitrification to mitigate nitrate leaching and nitrous oxide emissions in grazed grassland: a review Journal of Soils and Sediments, 16: 1401–1420.

Draganova, I., I. Yule, M. Stevenson and K. Betteridge (2016) The effects of temporal and environmental factors on the urination behaviour of dairy cows using tracking and sensor technologies. Precision Agriculture, 17: 407–420.

Hoogendoorn, C. J., K. Betteridge, S.F. Ledgard, D.A. Costall, Z.A. Park and P.W. Theobald (2011)

Nitrogen leaching from sheep-, cattle- and deer-grazed pastures in the Lake Taupo catchment in New Zealand. Animal Production Science, 51(5): 416–425.

Hoogendoorn, C. J., P. C. D. Newton, B. P. Devantier, B. A. Rolle, P. W. Theobald and C. M. Lloyd-West (2016) Grazing intensity and micro-topographical effects on some nitrogen and carbon pools and fluxes in sheep-grazed hill country in New Zealand. Agriculture, Ecosystems and Environment, 217: 22–32.

Hirata, M., M. Higashiyama and N. Hasegawa (2011) Diurnal pattern of excretion in grazing cattle. Livestock Science, 142(1-3): 23–32.

Hutchings, N. J., J. E. Olesen, B. M. Petersen and J. Berntsen (2007) Modelling spatial heterogeneity in grazed grassland and its effects on nitrogen cycling and greenhouse gas emissions. Agriculture, Ecosystems and Environment, 121: 153–163.

Kawamura, K., K. Betteridge, I.D. Sanches, M.P. Tuohy, D. Costall and Y. Inoue, (2009) Field radiometer with canopy pasture probe as a potential tool to estimate and map pasture biomass and mineral components: a case study in the Lake Taupo catchment New Zealand Journal of Agricultural Research, 52: 417–434.

Kawamura, K., A. D. Mackay, M. P. Tuohy, K. Betteridge, I. D. Sanches and Y. Inoue (2011) Potential for spectral indices to remotely sense phosphorus and potassium content of legume-based pasture as a means of assessing soil phosphorus and potassium fertility status. International Journal of Remote Sensing, 32: 103–124.

Kawamura, K., Y. Sakuno, Y. Tanaka, H-J Lee, J. Lim, Y. Kurokawa and N. Watanabe (2011) Mapping herbage biomass and nitrogen status in an Italian ryegrass (*Lolium multiflorum* L.) field using a digital video camera with balloon system. Journal of Applied Remote Sensing, 5: 1–11.

Kawamura, K. and A. Akiyama (2012) Remote sensing for precision grassland management. Journal of the Remote Sensing Society of Japan, 32: 232–244. (in Japanese)

Lambert, M. G., Clark, D. A., Mackay, A. D., Costall and D. A. (2000) Effects of fertiliser application on nutrient status and organic matter content of hill soils. New Zealand Journal of Agricultural Science, 43: 127–138.

Lambert, M. G., A. D. Mackay, B. P. Devantier, D. B. McDougall, D. J. Barker and G. Park-Ng (2003) Redefining the production potential of hill pastures using fertiliser nitrogen. Proceedings of the New Zealand Grassland Association, 65: 35–40.

Ledgard, S.F. (2001) Nitrogen cycling in low input legume-based agriculture, with emphasis on legume/grass pastures Plant and Soil, 228: 43–59.

Li, F.Y., K. Betteridge, R. Cichota, C.J. Hoogendoorn and B.H. Jolly (2012a) Effects of nitrogen load variation in animal urination events on nitrogen leaching from grazing systems. Agricultural Ecosystems and Environment, 159: 81–89.

Li, F. and K. Betteridge (2012b) Assessing the effectiveness of applying nitrification inhibitor in stockcamps for mitigating nitrogen loss from grazed pastures. In Advanced Nutrient Management: Gains from the Past - Goals for the Future, L.D. Currie and C. L. Christensen (Eds), Occasional Report No. 25. Fertilizer and Lime Research Centre, Massey University, Palmerston North, New Zealand. 10 pages.

Lilienthal, H., A. Brauer, K. Betteridge and E. Schnug (2007) Monitoring land use change in the Lake Taupo catchment between 1975, 1990 and 2002 using satellite remote sensing data. Proceedings of the New Zealand Grassland Association, 69, pp.17–22.

McDowell, R. W. (2006) Phosphorus and sediment loss in a catchment with winter forage grazing off cropland by dairy cattle. Journal of Environmental Quality, 35(2): 575–583.

McDowell, R. W., M. S. Srinivasan (2009) Identifying critical source areas for water quality: 2. Validating the approach for phosphorus and sediment losses in grazed headwater catchments. Journal of Hydrology, 379: 68–80.

McGechan, M. B. and Topp, C. F. E., (2004) Modelling environmental impacts of deposition of excreted nitrogen by grazing dairy cows. Agricultural Ecosystems and Environment, 103: 140–164.

Misselbrook, T., C. Umstätter, C. A. Duthie, L. Nicoll and T. Waterhouse (2013) Automated monitoring of urination events from grazing beef cows. Precision Livestock Farming 2013 — Papers Presented at the 6th European Conference on Precision Livestock Farming, ECPLF 2013, Katholieke Universiteit Leuven, pp.211–216.

Misselbrook, T., H. Fleming, V. Camp, C. Umstätter, C. A. Duthie, L. Nicoll and T. Waterhouse (2016)

Automated monitoring of urination events from grazing cattle. Agriculture Ecosystems & Environment, 230: 191–198.

Monaghan, R. M., M. J. Hedley, H. J. Di, R. W. McDowell, K. C. Cameron and S.F. Ledgard (2007) Nutrient management in New Zealand pastures: recent developments and future issues. New Zealand Journal of Agricultural Research, 50: 181–201.

Orr, R. J., B. A. Griffith, R. A. Champion and J. E. Cook (2012) Defaecation and urination behaviour in beef cattle grazing semi-natural grassland. Applied Animal Behaviour Science, 139: 18–25.

Parfitt, R. L., A .D. Mackay, D. J. Ross and P. J. Budding (2009) Effects of soil fertility on leaching losses of N, P and C in hill country. New Zealand Journal of Agricultural Research, 52: 69–80.

Ravera, B. L., R. H. Bryant, K. C. Cameron, H. J. Di, G. R. Edwards and N. Smith (2015) Use of a urine meter to detect variation in urination behaviour of dairy cows on winter crops. Proceedings of the New Zealand Society of Animal Production 75 pp. 84–88.

Roche, J. R., S. F. Ledgard, M. S. Sprosen, S. B. Lindsey, J. W. Penno, B. Horan and K. A. Macdonald (2016) Increased stocking rate and associated strategic dry-off decision rules reduced the amount of nitrate-N leached under grazing. Journal of Dairy Science, 99 (7): 5916–5925.

Romera, A. J., G. Levy, P. C. Beukes, D. A. Clark and C. B. Glassey (2012) A urine patch framework to simulate nitrogen leaching on New Zealand dairy farms. Nutrient Cycling in Agroecosystems, 92(3): 329–346.

Rowarth, J. S., Gillingham, A. G., Tillman, R. W. and Syers, J. K. (1992): Effect of phosphate fertiliser addition and land slope on soil phosphate fractions. New Zealand Journal of Agricultural Research, 35: 321–327.

Saggar, S., A. D. Mackay, M. J. Hedley, M.G. Lambert and D.A. Clark (1990) A nutrient transfer model to explain the fate of phosphorus and sulphur in a grazed hill-country pasture. Agriculture Ecosystems & Environment, 30: 295–315.

Selbie, D. R., L. E. Buckthought and M. A. Shepherd (2015) The Challenge of the Urine Patch for Managing Nitrogen in Grazed Pasture Systems. Advances in Agronomy, 129: 229–292.

Shepherd, M. A., G. Brendon, G. Welten, D. Costall, P. G. P. Cosgrove, M. Pirie and K. Betteridge (2016) Evaluation of refractive index for measuring urinary nitrogen concentration in a sensor worn by grazing female cattle. New Zealand Journal of Agricultural Research: DOI: 10.1080/00288233.2016.1237979.

Shorten, P. R. and A. B. Pleasants (2007) A stochastic model of urinary nitrogen and water flow in grassland soil in New Zealand, Agriculture, Ecosystems and Environment, 120 (2-4): 145–152.

White, S. L., R. E. Sheffield, S. P. Washburn, L. D. King and J. T. Green Jr (2001) Spatial and time distribution of dairy cattle excreta in an intensive pasture system. Journal of Environmental Quality, 30: 2180–2187.